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The President and Fellows
of Harvard University
Office of Sponsored Research
Holyoke Center, Rm 440
Attn: Dr. Robert Westervelt,
Principle Investigator
1350 Massachusetts Avenue
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Subj: CONTRACT No. N00014-84-K-0329 FINAL TECHNICAL REPORT

Dear Dr. Westervelt:

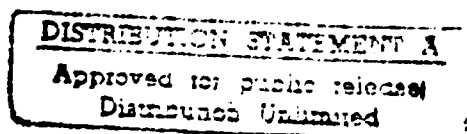
Subject contract completed on 30 June 1989. The contract requires the final technical report to be submitted within sixty (60) days of contract completion. I have no evidence that such a report was ever submitted. I request that you take action to furnish my office with a final technical report.

It is requested that your office take urgent and prompt action to rectify the situation no later than 11 January 1991.

If you have any questions concerning this matter, please give me a call at (617) 258-1394.

Sincerely Yours,
Monique B. Dillon
Monique B. Dillon
Procurement Assistant

cc: Merily Sterns, Senior Assistant Director, Cambridge, MA.
Michael Shliesinger, Code 1112, Scientific Officer, VA.
Patent Counsel, OOCCL1, Code 11D4, Arlington, VA.



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FINAL TECHNICAL REPORT FOR THE OFFICE OF NAVAL RESEARCH

TITLE: Nonlinear Dynamics in Semiconductors

CONTRACT NUMBER: N00014-84-K-0329

PRINCIPAL INVESTIGATOR: Prof. Robert M. Westervelt
Division of Applied Sciences
Harvard University
Cambridge, MA 02138

ORGANIZATION: President and Fellows of Harvard College
Office of Sponsored Research
Holyoke Center
Harvard University
Cambridge, MA 02138

DATE OF COMPLETION: 30 June 1989

FOR THE ATTENTION OF: Dr. Michael Shlesinger
Office of Naval Research
Code 412 (Physics)
800 North Quincy Street
Arlington, VA 22217

ENDORSEMENTS:



R.M. Westervelt, Principal Investigator

A. Gold, Associate Dean for Administration
Division of Applied Sciences

Authorized Institutional Representative

TABLE OF CONTENTS

I.	Research Progress	
A.	Dynamics of Space Charge Domains in Semiconductors	3
B.	Universal Structure of Frequency Locking	3
C.	Dynamics of Electronic Neural Networks	4
D.	Collective Dynamics of Coupled Oscillators	4
E.	Investigations of 1/f Noise	4
II.	Resume of Principal Investigator	5
III.	Publications, Ph.D. Theses, and Invited Talks Supported by Contract	6

Statement "A" per telecon Dr. Michael Shlesinger
ONR/Code 1112

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I. RESEARCH PROGRESS

In the past three years we have made important progress in our understanding of the dynamics of space charge domains in cooled photoconductors, in experimental tests of the universal structure of frequency locking in driven oscillators, and in the dynamics of electronic neural networks. In addition, we have investigated a number of different approaches to the problem of $1/f$ noise. In this section we will briefly summarize some of our results.

A. Dynamics of Space Charge Domains in Semiconductors

Stephen Teitsworth received his Ph.D. in 1986, and continued to work in my group for two years afterward, one supported by the ONR. He also was awarded an I.B.M. fellowship in recognition of his achievements. For his thesis, titled "Nonlinear Dynamics of Electrical Conduction in Extrinsic Photoconductors", he presented experimental work on the dynamics of extrinsic Ge photoconductors. For much of this experimental work, the photoconductor can be modelled as a single nonlinear oscillator with one degree of freedom. However, our experiments led us to believe that the physical picture was really more complex. In his thesis, Stephen also presented a careful theoretical analysis of the dynamics of moving space charge domains in extrinsic semiconductors, which we predicted would cause the damped ringing transient response as well as active oscillations observed in Ge devices. This analysis is in good agreement with the original experimental data, taken without spatial resolution. To test some of these ideas we have started new measurements of the spatio-temporal dynamics of space charge domains with both spatial and temporal resolution, described below. Stephen's work has appeared as publications 2, 3, 8, 9, 10, 12 below, as well as his thesis, and has been the subject of a quite a number of invited talks, including the 9th International Conference on Noise in Physical Systems. Stephen has recently accepted a position as an Assistant Professor in the Physics Department of Duke University. A graduate student, Andrew Kahn, has worked with Stephen for the past two years and is taking over this research with the aid of a new graduate student, Douglas Mar, who is supported by an AT&T Bell Scholarship.

B. Universal Structure of Frequency Locking

Using extrinsic Ge photoconductors as driven nonlinear oscillators, we have made a series of high precision tests of universal predictions for the structure of frequency locking. Because these predictions are universal, they are broadly applicable to wide range of experimental systems including fluids and mechanical oscillators as well as semiconductors. Beth Gwinn received her Ph.D. in 1987 for her work on this problem, and was supported in part by an AT&T Bell Scholarship. Her thesis is titled "Quasiperiodicity and Frequency Locking in Electrical Conduction in Ge", and the results have also appeared in publications 7, 9, 11, and 13. Beth had also worked on the effects of fractal basin boundaries for the driven damped pendulum, publication 4, as well as publications supported by the previous grant. At present Beth is a postdoc in my group working on semiconductors in strong magnetic fields, supported by the N.S.F.

This experimental work established that the universal structure of frequency locking discovered using a sine circle map is applicable to real experimental systems with an unprecedented degree of precision. Beth found that *both* the frequencies and the amplitudes of peaks in the power spectrum of a driven Ge oscillator agree with the universal predictions of circle map theory at the critical line where the system becomes chaotic. In later work she was able to measure the spectrum of exponents $f(\alpha)$ for this case, again using a Ge photoconductor. This spectrum agreed with universal theory to within $\sim 1\%$, with no adjustable parameters. These latter measurements were particularly difficult, and in the course of the analysis, we discovered a number of important properties of $f(\alpha)$, including the effects of external noise, as well as the limitations imposed by a finite data set.

C. Dynamics of Electronic Neural Networks

Electronic neural networks have been proposed as an alternative method of performing high speed, fault tolerant associations and pattern recognition. This field has experienced phenomenal growth over the past few years, and hardware implementations of various types of networks are now being made in VLSI circuits. A problem which is critically important for hardware is the stability of the network when the individual neurons have finite temporal response. Over the past three years we have investigated the types of instabilities which can occur and we have developed criteria for to avoid instability. This work was also funded through the Joint Services Electronics Program at Harvard.

Ken Babcock, a graduate student working on this problem, showed that even simple networks composed of a few neurons, could exhibit a variety of complex phenomena characteristic of nonlinear dynamical systems including chaos, other types of instability, and very long transients when the neurons had finite temporal response or time delay. This work was presented in publications 1, 5, and 6. A new graduate student, Charlie Marcus, supported by an AT&T Bell Scholarship, then undertook a systematic study of the effects of network topology and delay time on the stability of feedback networks. Charlie studied the effects of overcrowding on the shapes of the basins of attraction for stored memories in Hopfield networks, and the appearance of collective oscillations in networks with sufficiently long delay, using analysis, numerical simulations, and experiments on a real network with 8 neurons (publication 14). He then systematically developed a series of stability criteria for feedback networks with time delay which establish design criteria for networks of different topology, presented in publication 17. We hope that this latter paper in particular will be of real use to those designing hardware networks. Both Ken and Charlie are currently working in my group.

D. Collective Dynamics of Coupled Oscillators

Charlie Marcus has also been involved in a new project with an N.S.F. postdoctoral fellow, Steven Strogatz: a study of the collective dynamics of coupled oscillators with random pinning. This model has application to a variety of important natural phenomena including charge density wave (CDW) transport and the origins of friction. Steven and Charlie showed that a number of phenomena observed for CDW's including hysteretic "sticking" and a time delay before the onset of conduction arose naturally from the collective properties of the model. This work has appeared in publications 15, and 18 including a recent Physical Review Letter. Steve Strogatz is continuing to work on this project this year.

E. Investigations of $1/f$ Noise

We have also continued to investigate possible origins of $1/f$ noise from dynamics in different contexts. Stephen Teitsworth showed that extrinsic photoconductors generate low frequency noise due to switching between different modes of conduction near breakdown, and that this noise could be eliminated by locking the sample to a strong a.c. drive (publication 12). This result could have important applications. In N.S.F. supported experiments, Alex Rimberg showed that the intensity power spectrum of multiply scattered coherent light from diffusing polystyrene spheres in water is $S(f) \propto 1/f^{1.5}$ at high frequencies and approximates $1/f$ over two decades. This result also applies to other situations where interfering waves are multiply scattered from moving scatterers.

II. Resume of Principal Investigator

Robert M. Westervelt

born October 9, 1949, in Philadelphia, Pennsylvania

Division of Applied Sciences and Department of Physics
Harvard University
Cambridge, MA 02138
telephone (617) 495-3296

Field of Research

Experimental Semiconductor and Condensed Matter Physics -
Nonlinear dynamics and chaos in semiconductors.
Semiconductor transport in strong magnetic fields.

Education

B.S. in Physics, 1971, California Institute of Technology
Ph.D. in Physics, 1977, University of California at Berkeley
A.M., Hon., 1986, Harvard University

Employment

1986 to present	Gordon McKay Professor of Applied Physics and Professor of Physics, Harvard University
1984 to 1986	Associate Professor of Physics and Applied Physics Harvard University
1979 to 1984	Assistant Professor of Physics and Applied Physics Harvard University

Honors and Affiliations

Member of JASON
Co-Chairman, Gordon Conference on Condensed Matter Physics, 1988.
Board of Editors, Physica D - Nonlinear Phenomena, 1986 - present.
Member, Office of Naval Research Options Review Panel, 1984.
Ross N. Tucker Memorial Award, Intel Corporation, 1977.
Member, American Physical Society, 1971 - present.
Chancellor's Fellowship, University of California, Berkeley, 1971.
Graduated with Honor, third in class, California Institute of Technology, 1971.

III. PUBLICATIONS, Ph.D. THESES, AND INVITED TALKS RELATED TO ONR SUPPORTED RESEARCH

Publications-

1. K.L. Babcock and R.M. Westervelt, "Dynamics of Simple Electronic Neural Networks", *Physica* **28D**, 305 (1987).
2. R.M. Westervelt and S.W. Teitsworth, "Nonlinear Dynamics and Chaos in Extrinsic Photoconductors", *Physica* **23D**, 187 (1986).
3. S.W. Teitsworth and R.M. Westervelt, "Nonlinear Current Voltage Characteristics and Spontaneous Current Oscillations in p-Ge", *Physica* **23D**, 181 (1986).
4. E.G. Gwinn and R.M. Westervelt, "Horseshoes in the Damped Driven Pendulum", *Physica* **23D**, 396 (1986).
5. K.L. Babcock and R.M. Westervelt, "Stability and Dynamics of Simple Electronic Neural Networks with Added Inertia ", *Physica* **23D**, 464 (1986).
6. K.L. Babcock and R.M. Westervelt, "Complex Dynamics in Simple Neural Circuits", in *Proc. Conf. Neural Networks for Computing*, Snowbird Utah, (A.I.P. Conference Series, 1986), p.23.
7. E.G. Gwinn and R.M. Westervelt, "Frequency Locking, Quasiperiodicity, and Chaos in Extrinsic Ge", *Phys. Rev. Lett.* **57**, 1060 (1986); (E) *Phys. Rev. Lett.* **59**, 247 (1987).
8. S.W. Teitsworth and R.M. Westervelt, "Nonlinear Dynamics of Extrinsic Ge Photoconductors", in *Proc. 18th Int. Conf. Physics of Semiconductors*, Stockholm, 1986, vol. 2, (World Scientific, Singapore, 1986), 1551.
9. R.M. Westervelt, S.W. Teitsworth, and E.G. Gwinn, "Chaotic Dynamics in Ge Photoconductors", in *Proc. Conf. Fundamental Effects in Semiconductors*, Copenhagen, 1986, *Physica Scripta* **T14**, 65 (1986).
10. S.W. Teitsworth, B.A. Lynn, and R.M. Westervelt, "Chaotic Dynamics in a Simple Model of Extrinsic Photoconductors", in *Proc. Conf. Fundamental Effects in Semiconductors*, Copenhagen, 1986, *Physica Scripta* **T14**, 71 (1986).
11. E.G. Gwinn and R.M. Westervelt, "Scaling Structure of Attractors at the Transition from Quasiperiodicity to Chaos in Electronic Transport in Ge", *Phys. Rev. Lett.* **59**, 157 (1987).
12. S.W. Teitsworth and R.M. Westervelt, "Chaos and Noise in Semiconductor Devices: Noise Scaling and Noise Suppression", in *Proc. 9th Int. Conf. on Noise in Physical Systems*, Montreal, 1987, accepted for publication.
13. R.M. Westervelt, E.G. Gwinn, and S.W. Teitsworth, "Chaotic Dynamics in Ge Photoconductors", in *Proc. "Chaos 87"*, Monterey CA, 1987, (North Holland, Amsterdam), p.37.
14. C.M. Marcus and R.M. Westervelt, "Basins of Attraction for Electronic Neural Networks", in *Neural Information Processing Systems*, Denver, 1987, Dana Z. Anderson ed. (American Inst. of Physics, New York, 1988), p. 524.

15. A.J. Rimberg and R.M. Westervelt, "Temporal Fluctuations in Multiply-Scattered Light in a Random Medium", Phys. Rev. **B38**, 5073 (1988), [supported by N.S.F].
16. S.H. Strogatz, C.M. Marcus, R.M. Westervelt, and R.E. Mirollo, "Solvable Model of Charge-Density Wave Dynamics with Phase Slippage", Phys. Rev. Lett. **61**, 2380 (1988).
17. C.M. Marcus and R.M. Westervelt, "Stability of Analog Neural Networks with Delay", Phys. Rev. A **39**, 347 (1989).
18. S.H. Strogatz, C.M. Marcus, R.M. Westervelt, and R.E. Mirollo, "Collective Dynamics of Coupled Oscillators with Random Pinning", Physica D **36**, 20 (1989).
19. C.M. Marcus and R.M. Westervelt, "Dynamics of Iterated Map Neural Networks", Phys. Rev. A **40**, 501 (1989).
20. C.M. Marcus and R.M. Westervelt, "Dynamics of Analog Neural Networks with Time Delay", in *Advances in Neural Information Processing Systems*, Edited by D.S. Touretzky (Morgan Kaufman, San Mateo, California, 1989), p. 568.
21. C.M. Marcus, S.H. Strogatz, and R.M. Westervelt, "Delayed Switching in a Phase-slip Model of Charge-density Wave Transport", Phys. Rev. B **40**, 5588 (1989).
22. K.L. Babcock and R.M. Westervelt, "Elements of Cellular Domain Patterns in Magnetic Garnet Films", Phys. Rev. A **40**, 2022 (1989).
23. K.L. Babcock and R.M. Westervelt, "Topological Melting of Cellular Domain Lattices in Magnetic Garnet Films", Phys. Rev. Lett. **63**, 175 (1989).
24. S.H. Strogatz and R.M. Westervelt, "Predicted Power Laws for Delayed Switching of Charge-Density Waves", Phys. Rev. B **40**, 10501 (1989).

Ph.D. Theses Supervised

- S. W. Teitsworth, "Nonlinear Dynamics of Electrical Conduction in Extrinsic Photoconductors", Harvard University, 1986.
- E. G. Gwinn, "Quasiperiodicity and Frequency Locking in Electrical Conduction in Ge", Harvard University, 1987.
- K.L. Babcock, "Cellular Domain Patterns in Magnetic Garnet Films", Harvard University, 1989.

Invited Talks (R.M. Westervelt)

1. Greater Washington Condensed Matter Physics Colloquium, Washington DC, 3/6/86, "Nonlinear Dynamics and Chaos in Semiconductors".
2. Naval Research Laboratory, 3/7/86, "Nonlinear Dynamics and Chaos in Extrinsic Photoconductors".
3. Duke University, 3/10/86, "Nonlinear Dynamics in Semiconductors".
4. University of Illinois, 4/23/86, "Nonlinear Dynamics and Chaos in Semiconductors".
5. Tutorial on Chaos for Science Writers (with P. Hohenberg), Washington Meeting of the American Physical Society, 4/28/86.
6. Satellite Conference to International Conference Physics of Semiconductors, "Fundamental Effects in Semiconductor Systems", Copenhagen, 8/6/86 to 8/8/86, "Chaotic Dynamics of Ge Photoconductors".
7. Gordon Conference on Fractals, New Hampshire, 8/18/86 to 8/22/86, "Fractal Basin Boundaries and Intermittency".
8. University of South Carolina, 11/13/86, "Chaotic Dynamics of Ge Photoconductors".
9. Brown University, 12/1/86, "Chaotic Dynamics of Ge Photoconductors".
10. Conference "Chaos 87", Monterey CA, 1/12/87 to 1/14/87, "Chaotic Dynamics in Semiconductor Transport".
11. Neural Networks for Computing, Snowbird Utah, 4/1/87 to 4/3/87, "Nonlinear Dynamics of Electronic Neural Networks".
12. Annual Meeting California Coordinating Committee for Nonlinear Studies, Univ. of California Santa Cruz, 3/25/88 to 3/26/88, "Dynamics of High-electric-field Domains in Ge".
13. Neural Networks for Computing, Snowbird Utah, 4/6/88 to 4/9/88, "Stability of Neural Networks with Time Delay".
14. Princeton University, 4/26/88, "Dynamics of High-electric-field Domains in Ge".
15. Neural Networks for Computing, Snowbird Utah, 4/4/89 to 4/8/89, "Stability of Neural Networks with Delay".
16. Spring School on Experimental Nonlinear Dynamics, Tianjin, China, 5/8/89 to 5/12/89, "Nonlinear Dynamics in Semiconductors"; "Pattern Formation of Magnetic Domains".
17. Beijing University, 5/14/89, "Experimental Tests of Universal Circle Map Theory".